High Power Ultrasonic Waves in Water

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Thesis

HIGH POWER ULTRASONIC WAVES IN WATER

by

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Approved

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OUTLINE OF THE THESIS

ILLUSTRATIONS

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I wish to express my appreciation to Dr. Royal M. Frye and Mr. Ward Low of Boston University Graduate School Physics Department for their helpful criticism in the preparation of the thesis. I also express my appreciation to Mr. B. B. Drisko of Stevens Arnold Company for his assistance and willingness to help in the solution of the many technical problems that arose and to Mr. Diggins and other employees of Stevens-Arnold Company for assistance in the work.

INTRODUCTION

The maximum desired peak power of a sound wave transmitted through a liquid is limited by the presence of what is termed cavitation. Cavitation by definition is applied to the liberation from the liquid of bubbles of air or other absorbed gases and to the tearing apart of the liquid itself due to high stresses produced.

The power level at which cavitation begins is about 0.03[1] watts/centimeter square for water at atmospheric pressure when transmitting sound under steady-state conditions, but the amount of power that water can transmit increases rapidly as the pulse length is shortened. An attempted investigation of this phenomenon using pulses varying from 0.3 to 10 microseconds shows that water has some nonlinear characteristics other than cavitation that limits the power. Cavitation as it has been defined was not detected.

1. Cady, W.G., Piezoelectricity, P. 683, McGraw-Hill, 1946.

HISTORICAL REVIEW

The limitation produced by cavitation upon power transmitted by a liquid was first investigated by Boyle[1] and his associates. They found that if they assumed only the hydrostatic pressure (p_o) as a preventative of cavitation in the liquid, the maximum power transmitted per square centimeter would be $p_o^2/2\rho c$ where ρ is the density of the medium and c the velocity of the sound. Experiments gave a much lower value and also showed that cavitation was more readily produced in volatile liquids. Upon taking vapor pressure (p_v) into account, the maximum power per square centimeter would be $(p_o-p_v)^2/2\rho c$. Measurements with a torsion pendulum gave still lower energy levels to produce cavitation. Boyle observed that the bubbles accompanying cavitation appeared to form from the union of microscopically small bubbles already in the liquid. Two further causes of bubble formation appeared to result from the negative pressure set up in the liquid which lead to the emergence of the gas dissolved and from the tearing apart of the liquids due to high stress placed on the liquid. There is some controversy as to whether all three types of bubble formation can be grouped under the term cavitation.

A recent investigation of the properties of liquids at

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1. Boyle, R.W., Trans. Roy. Soc., Canada 16, 293 (1922)

high sound pressures by H.B. Briggs, J.B. Johnson, and N.P. Mason[1] has shown that cavitation depends upon cohesive pressure, tensile strength, and the ambient pressure. The power required to produce cavitation was found to increase rapidly as the pulse length was shortened. An explanation of the phenomena was based upon Eyring's[2] theory of viscosity, plasticity, and diffusion. The increase in power with decreasing pulse length is assumed to result from a time lag in the formation of the bubbles which originate from natural holes in the liquid, possibly molecular in size.

APPARATUS

The experimental procedure required the development of short square pulses of energy that can be converted into sound waves by the use of a piezoelectric transducer. Equipment that could be used after some modification was developed by M.I.T. Radiation Laboratory and was loaned to Boston University by Stevens-Arnold Company, Boston, Mass. A block diagram of the equipment as set up for measurements is shown in Figure 6. A photograph of the equipment as it was set up at Stevens-Arnold Company is shown in Figure 8. The experimental set-up was essentially the same while work was being

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1. Briggs, H.B., Johnson, J.B., and Mason, W.P.,"Properties of Liquids at High Sound Pressure," Journal Acoustical Society of America, V. 19, 4, July 1947.

2. Eyring, H., Journal Chemical Physics, 4, 283, (1936)

done at Boston University.

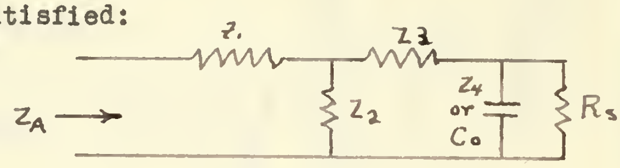
The crystal driver is a modified 15 megacycle R-2A crystal driver described in full (as it was originally constructed) by S. Frankel in a Radiation Laboratory report.[1] It was converted to produce 10 megacycles (later changed to 15 megacycles) capable of being pulsed by an external pulse generator, Model 79-B, Boontoon Serial #444. A complete circuit diagram of the modified R-2A crystal driver is shown in Figure 12. The wave is generated by a shock excited Hartley oscillator. The duration of the oscillation is determined by the pulse input. The pulsed oscillation is fed to the driver amplifier which drives the power amplifier VT(5). The power output of the driver is determined by the plate and screen voltage that is supplied to the power amplifier. Screen and plate voltage is supplied by a high voltage power supply, Figure 14, which produces 2000 volts for the plate and 1000 volts for the screen. For testing purposes plate and screen voltages are cut down to 900 and 550 volts respectively. The high voltage supply is unregulated, therefore the power output of the crystal driver varies with pulse length and prf. (pulse repetition rate). The power supply for the other tubes of the crystal driver, Figure 15, is regulated with the exception of the 550 volt output. The power output of the crystal driver is controlled by an attenuator box which

1. Frankel, S., RL 645-8, "The R-1 and R-2 Crystal Drivers", Radiation Laboratory, M.I.T., February 1946.

contains resistance pads designed for 70 ohms input impedance. Each pad is calibrated in decibels and can be switched in or out. The two attenuators (one for transmitter and one for receiver circuits) can be seen in Figure 8.

The interconnection of units with 76 ohm (RG-6/U) coaxial cable made necessary impedance matching networks. In the transmitter the plate coil of the 829 is tapped as shown in the circuit diagram of the R-2 crystal driver. At the crystal two types of matching networks are used. The measurement on 10 megacycles was made using tapped coils. This was believed to be inefficient and was discarded in favor of regular transformers. No data were taken on 10 megacycles using the regular transformers because of the lack of 10 megacycle crystals. The data at 15 megacycles were taken using transformer matching networks. The tapped coil is designed as a half wave transformer shown in Sketch 1.

If the following relationships are satisfied:



Sketch 1.

$z_2 + z_3 + z_4 = 0$

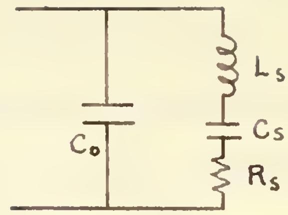
and $z_1 + z_2(1 + z_2/z_4) = 0$

where $z_4 = -\dfrac{j}{\omega C_o}$; then the equation for impedance match in a tapped coil follows:

$z_A = (z_2/z_4)^2 R_s$.

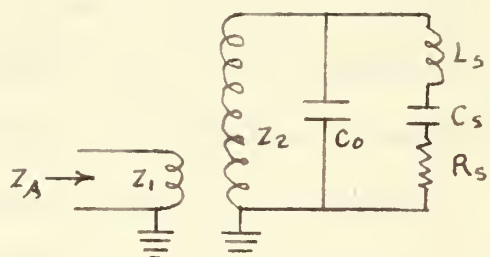
From this if z_1 is made capacitive and the elements z_2 and z_3 are the two branches of a tapped coil, the conditions will be met. If this is to properly match the equivalent electrical network of the crystal, Sketch 2, then z_2 and z_3 must tune to the capacity C_o of the crystal. The capacity z_1 must tune to

the series resonance with z_2 plus a mutual inductance term. It was found that this capacity could be left off for the coils used on 10 megacycles. The value of R_s was determined approximately experimentally by replacing the crystal with a condenser and a resistance of 14,000 ohms.



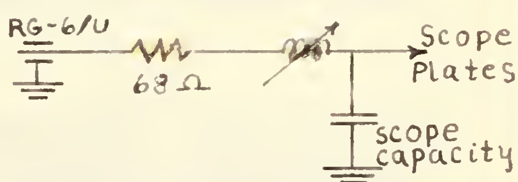
Sketch 2

For the regular transformer type of matching network shown in Sketch 3 terminated with the equivalent electrical network of the crystal, the secondary was adjusted to tune the C_o of the crystal network. The turn ratio was determined the same as with the tapped coils. $z_A = (z_1/z_2)^2 R_s$. The R_s was determined by substitution again and is about 10,000 ohms for 15 megacycles.



Sketch 3

The scope matching network, Sketch 4, matched the scope to the coaxial cable and produced a voltage gain of about 13 decibels. This network was used only to increase sensitivity of the scope. Where actual quantitative measurements were made this matching network was not used.



Sketch 4

The crystal holders were designed and built by Stevens-Arnold Company. Pictured in

Figures 9 and 10, they were constructed so that accurate adjustment of the azimuth and elevation could be made. One of them was calibrated with vernier scales to make possible the plotting of beam patterns. The crystals were mounted in a cartridge that plugged into the matching box of the crystal holder. Since the entire matching box was under water, it had to be constructed water-tight. The crystal cartridge used is described by S. Frankel and Rosenberg.[1] It is shown disassembled in Figure 11.

EXPERIMENTAL METHOD AND RESULTS

The method employed is one primarily of measuring absorption by point to point transmission in a tank of water. A known input voltage is applied to the transmitter crystal. The voltage produced by the receiving crystal is measured at varying distances from the transmitter. There was no effort to determine the attenuation constant since the nonlinear portions of the attenuation curves were of the most interest, although the linear portion of the curves agrees very well with the absorption of 65 decibels/ meter at 15 megacycles. The nonlinear portion of the curve has been reported as cavitation.[2]

1. Frankel, S. & Rosenberg, P.,"Supersonic Components for Use in Radar Trainer", RL 1050 Radiation Laboratory MIT, March 25, 1946.
2. Cefola, M., Droz, M.E., Frankel, S., Jones, E.M.,Maslach,G. Teeter, C.E., Jr., "An Application of the Pulse Technique to the Measurement of the Absorption of Supersonic Waves in Liquids", RL 963, Radiation Laboratory, MIT,March 30, 1946.

The voltages were measured on the synchroscope which has a voltage sensitivity of 70 volts/inch. All voltage measurements were made peak to peak. The power input to the water was obtained by measuring the voltage developed across the primary of the transmitting transducer matching network, the measurement being made after a 10:1 reduction in order to keep within the voltage limitation of the scope. Output power is measured by the voltage developed across a 70 ohm resistance which terminates the coaxial cable leading from the matching network of the receiving crystal. A 70 ohm attenuator box was used in the connecting cable to keep the received voltage within the limitation of the scope. In every case except for determining actual power received the scope matching network replaced the 70 ohm cable load resistance. Since only relative magnitudes were of interest for plotting the curves, there was no correction made for the 13 decibel gain. Input or output power can be calculated from the relation $W = \frac{E^2}{R}$ where E is read on the scope and R is 70 ohms.

A series of curves is shown in Figures 1 and 2. Both the input-output curves and the attenuation curves are plotted from the same set of data. The zero points on the input-output curves are only arbitrary reference points set so that the scales could be expressed in decibels. This reference for these curves was taken as 0.1 inch peak to peak deflection on the scope. The input scale is the decibel attenuation

introduced by the attenuators in the transmitter connecting cable. The flattening out of the curves at high power levels here cannot be due to cavitation effects or they would not be a function of the distance between the crystals. Also the wave form was not destroyed at these points as it is supposed to be at cavitation.[1] At the distance of 0.25 inch it can be seen that the input-output curve follows within experimental error the ideal curve drawn on the graph in dotted lines which has a 45° slope. If there were cavitation (as defined) present this could not be straight. A spreading of the beam pattern as a function of power level could result in an effect like this. Beam patterns were taken for a receiving crystal and a transmitting crystal at two power levels, Figure 7, in an effort to check whether there was any additional spreading of the beam at high power levels. These curves do not prove anything definite but there does not seem to be sufficient variation to account for the non-linearity of the input-output curves. Input-output curves, Figure 4, taken at 10 megacycles show the same type of characteristic as those at 15 megacycles. These were taken only as a test and were not intended to be used in a report, but since the equipment was changed and never set up on 10 megacycles again they are included to show the similar results as on 15 megacycles.

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1. Op. Cit., Briggs, Johnson, & Mason.

Sound absorption is defined by the equation $I = I_0 e^{-2\alpha x}$ where I is the intensity of the wave at any point x and I_0 is the intensity when $x = 0$. The α is the coefficient of absorption. If the logarithm of this equation is plotted against x, the curve will be a straight line. The absorption curves, Figure 2, are straight at low power levels, but at high powers the absorption follows another law.

A possible explanation can be based upon the chemistry of the water molecule. Water contains a large amount of molecular species formed by the aggregation of simple molecules. These can be changed by changes in pressure and temperature. Near the boiling point water is supposed to be completely changed to simple molecules. Energy is required to break down the molecular aggregate. It may be possible that sufficiently intense sound waves would also break down the water into a purely molecular form with absorption of some of the sound energy. This effect will explain the results observed in the absorption curves and input-output curves. It will also explain one other effect noticed during measurements that does not appear on the graphs. At high powers if the power input was cut off for a short time then turned back on, the received voltage falls from its value at the instant that the power is turned on to a somewhat lower value. After the received signal has become constant a small amount of attenuation can be switched into the transmitter with a resulting drop in the received signal. The received

signal in this case slowly rises to a new level which sometimes is very close to the value of the received signal before the attenuation was switched on.

Sample data of this effect at a distance of 3 inches between crystal faces follow:

Transmitter Attenuation	0 db	5 db
	Scope Deflection	
Instantaneous Value of Signal	13	9.0
Steady Value of Signal	12	11.5

The amount of power absorbed by changing the form of the water would be a function of the volume of water in the beam. Due to the unidirectional drift or hydrodynamic flow, the water in the beam is being changed continuously and at a steady rate for any one power level; therefore the volume of water that is being subjected to change is a constant for any one power level. It takes time for the drift to be set up and to change, therefore any change in the power level would produce an instantaneous change in the received voltage, but this would change until the velocity of the unidirectional drift had reached a steady value. Then a constant volume of water would be subjected to the sound waves and a constant amount of power absorbed due to changing the molecular form of water.

The differences in the input-output curves are explained also by this since the closer the two crystals are together, the more power will be measured before it can be consumed in changing the molecular form of the water. When the crystals are one-quarter inch apart, the motion of the water is very

restricted by the crystal holders thus accounting for the straight line relationship at this distance.

In order to check the validity of the theory presented there was an attempt made to make input-output measurements near the boiling point. No results were obtained because of equipment failure at 60°C. The only noticeable difference using hot water was that the receiver signal did not change as recorded above. It was also noticed that the hydrodynamic flow was not as violent as it is in water at lower temperatures.

A tight fitting pipe was placed over the crystal cartridge to restrict the pumping action of the crystal. The results of an input-output curve with and without this restriction is shown in Figure 5. This curve does not prove anything definite since it is not known how the pipe placed over the crystal cartridge affects the electrical characteristics of the crystal. If this restriction changes the water loading of the crystal, then the curves are not accurate. If it has no effect on the loading, the curves are in agreement with the theory since the hydrodynamic flow is cut down with the pipe in place. Also in this test the received signal was steady.

Since the curve of Figure 5 with the pipe in place still has some bending, one other test was made to see if an increase in prf. would straighten out the curves. The possibility that this may happen was based on the theory that if some of the water molecules,that were broken down with the

absorption of sound, recombined before the next pulse was sent out, then the hydrodynamic flow would not be necessary in making the input-output curves non-linear. A prf. of 4000 cycles per second was used instead of the 1000 cycles per second as used in all the previous data. Again the equipment was not good enough to draw any definite conclusions. The change was so slight that it was inside the range of experimental error, although it was in the direction that would be expected assuming the above theory correct.

To check the above theory an accurate method of monitoring the input voltage must be developed such that any changes in the crystal driver output or changes in the water loading of the crystal can be eliminated as a possible error in measurements. Also changes in the crystal cartridge should be made in order to use it in hot water.

Calculation of the Power Level

To make the calculation of the power level at any point in the water the efficiency of the transmitting and receiving transducers with their associated matching networks must be determined. The method used in this work lends itself very readily to the measurement of the efficiency with a reasonable degree of accuracy. The efficiency was determined by extrapolating the absorption curves to zero in order to eliminate losses introduced by the water. Two absorption curves used to determine the efficiency are shown in Figure 3. The input

voltage was measured at the transmitter matching network as described previously. The output was the voltage developed across the aforementioned 70 ohm resistance. The efficiency is given by the formula Efficiency = $\frac{\text{Output}}{\text{Input}}(100)$. The efficiency measurement was made at two power levels.

High Power:

Output = 350 volts $\qquad \frac{350}{500}(100) = 70\%$

Input = 500 volts

Low Power: (15 decibels below the high power measurement.)

Output = 64 volts $\qquad \frac{64}{94}(100) = 68\%$

Input = 94 volts

The low power efficiency is more accurate since difficulty arises in extrapolating the high power curves to zero.

The extrapolation of the absorption curves was believed to be possible, since in every case the voltage difference in decibels between extrapolated points agrees within experimental error with the decibel difference in the input voltage.

The calculated efficiency is the efficiency of the transducers and their associated matching networks. In order to calculate the power in the water at any point, the efficiency of the receiving crystal and matching network must be known. Here both are assumed to be equally efficient, since both are identical in electrical and mechanical construction; therefore the receiver efficiency can be taken as about 82 per cent.

From the curves for efficiency measurements the power at 0.25 inch from the transmitter was calculated as follows:

E (peak to peak) = 236 volts

R = 70 ohms

$$E_{rms} = \frac{236}{2\sqrt{2}} = 83.5 \text{ volts}$$

$$W = \frac{E^2}{R}$$

$$W = \frac{(83.5)^2}{70} = 99 \text{ watts}$$

Taking the efficiency of the receiver into account:

$$W = \frac{99}{.82} = 120 \text{ watts.}$$

The power input to the water was calculated as follows:

E (peak to peak) = 500 volts

R = 70 ohms

$$E_{rms} = \frac{500}{2\sqrt{2}} = 177 \text{ volts}$$

$$W = .82 \; \frac{(177)^2}{70} = 355 \text{watts}$$

The diameter of the radiating crystal surface was 0.96 cm. or an area of 0.72 square centimeter. Therefore the above power measurements are 494 watts/ square centimeter transmitted and 167 watts/square centimeter received at a distance of 0.25 inch from the transmitter crystal.

DATA

d = distance between crystal faces in inches.

s = peak to peak deflection on scope in inches.

T_{db} = attenuation placed in transmitter lead cable in decibels.

R_{db} = attenuation placed in receiver lead cable in decibels.

Pulse length . . . . 2 micro-seconds

Prf. .1000 cycles per second

In table I the water temperature before taking data was 19.85°C.

In table I the water temperature after taking data was 20.10°C.

All measurements were made with 1 decibel more attenuation in transmitter than recorded.

TABLE I

d	7	6	5	4	3	2	1	.25
R_{db}	0	0	0	0	0	0	3	10
T_{db}	s	s	s	s	s	s	s	s
0	0.45	0.56	0.68	0.88	1.20	1.90	2.20	2.50
5	0.41	0.55	0.70	0.85	1.15	1.60	1.90	1.65
10	0.42	0.52	0.66	0.78	1.06	1.45	1.55	1.01
15	0.40	0.48	0.58	0.67	0.91	1.12	1.10	0.60
20	0.31	0.39	0.46	0.51	0.68	0.80	0.70	0.33
30	0.13	0.16	0.20	0.22	0.25	0.29	0.22	0.11
40		0.07	0.09	0.09	0.10	0.11	0.09	

TABLE II

d	7		6		5		4		3		2		1		.25	
T_{db}	s	s_{db}	s	s_{db}	s	s_{db}	s	s_{db}	s	s_{db}	s	s_{db}	s_c	s_{db}	s_c	s_{db}
0	0.45	13.1	0.56	15.0	0.68	16.6	0.88	18.9	1.20	21.6	1.90	25.6	3.16	29.6	7.90	38.0
5	0.41	12.9	0.55	14.8	0.70	16.9	0.85	18.6	1.15	21.2	1.60	24.2	2.67	28.6	5.46	34.8
10	0.42	12.5	0.52	14.4	0.66	16.4	0.78	17.8	1.06	20.5	1.45	23.3	2.18	26.8	3.16	30.0
15	0.40	12.0	0.48	13.6	0.58	15.3	0.67	16.5	0.91	19.2	1.12	21.0	1.56	23.8	1.90	25.6
20	0.31	9.8	0.39	11.8	0.46	13.3	0.51	14.2	0.68	16.6	0.80	18.0	0.99	20.0	1.07	20.6
30	0.13	2.3	0.16	4.1	0.20	6.2	0.22	6.8	0.25	8.0	0.29	9.2	0.31	9.9	0.34	10.8
40			0.07	-3.6	0.09	-1.9	0.09	-1.9	0.10	0	0.10	2.1	0.11	1.1		

The data in Table II which was used to plot the graphs was obtained from the data in Table I in the following way:

1) s was converted to decibels according to the formula $s_{db} = 20 \log \frac{s}{s_1} + R_{db}$ where s_1 is set at 0.10 since this is the smallest deflection that can be read with any degree of accuracy.

2) The true deflection s_c of s where R_{db} is other than zero was obtained from the formula $\text{antilog} \frac{s_{db}}{20} = s_c$.

TABLE III

Input	500V	94V
d	S	S
.25	236	60
.50	168	57
1	112	51
2	64	39
3	43	28
4	33	22
5	27	19

Table III gives the data for the absorption curves used in determining the efficiency and power.

TABLE IV

d	1		11		21	
T_{db}	s	s_{db}	s	s_{db}	s	s_{db}
4	2.91	29.3	0.91	19.2	0.47	13.4
10	1.70	24.6	0.77	17.7	0.40	12.0
14	1.10	20.6	0.61	15.7	0.34	10.6
24	0.40	12.0	0.27	8.6	0.16	4.1

Table IV gives the data taken at 10 megacycles. Here d is given in centimeters rather than in inches.

TABLE V

	A		B	
T_{db}	S	s_{db}	S	s_{db}
0	48	33.6	55	34.8
5	50	34.0	46	33.3
10	40	32.0	39	31.8
15	29	29.3	27.5	28.8
20	20	26.0	19	25.5
30	9	19.0	9	19.0

In Table V A = input-output data with no restriction and B = input-output data with pipe over the cartridge.

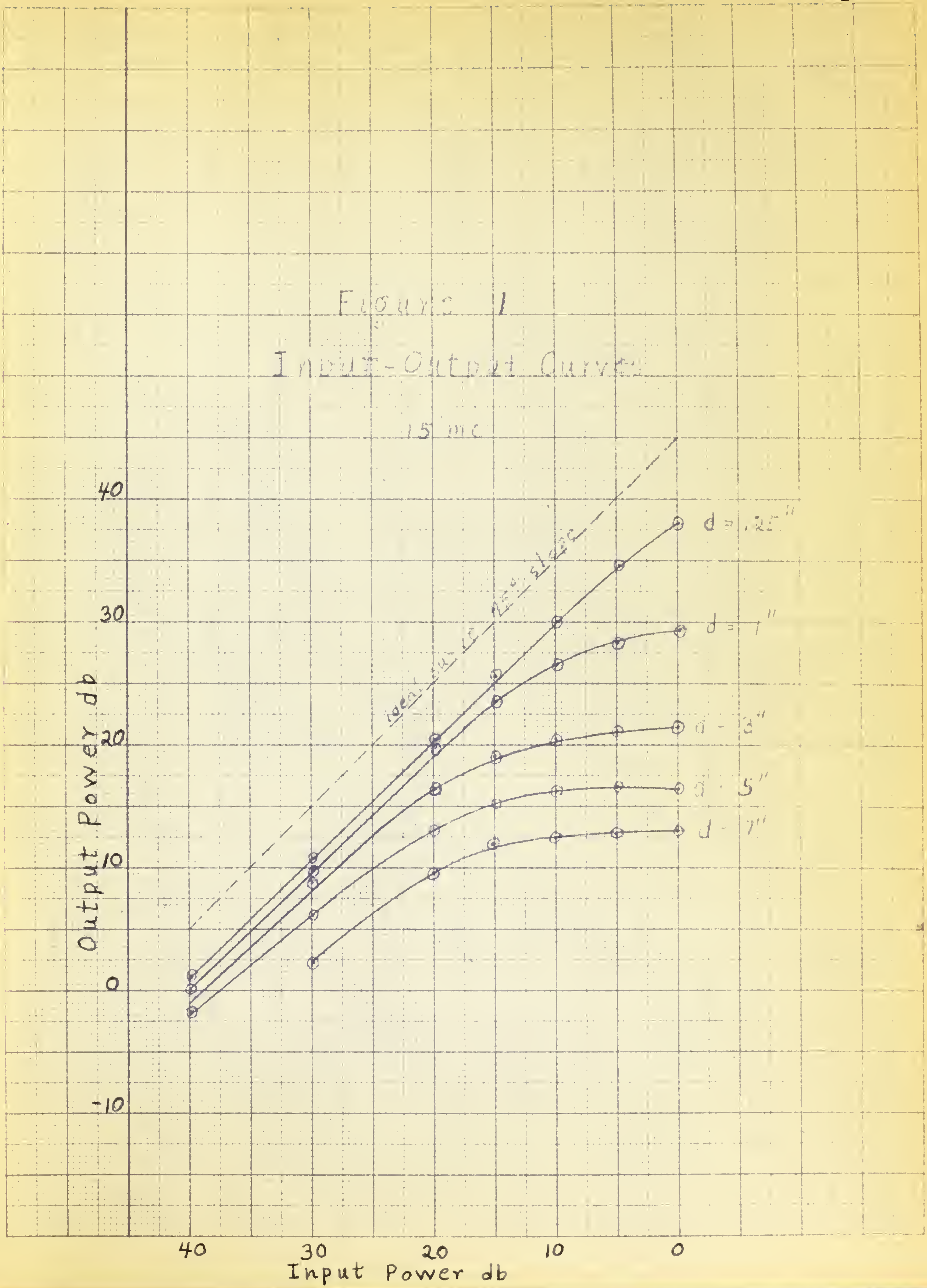


Figure 1
Input-Output Curves
15 mc
Output Power db
Input Power db
40
30
20
10
0
-10
40
30
20
10
0
d = .25"
d = 1"
d = 3"
d = 5"
d = 7"

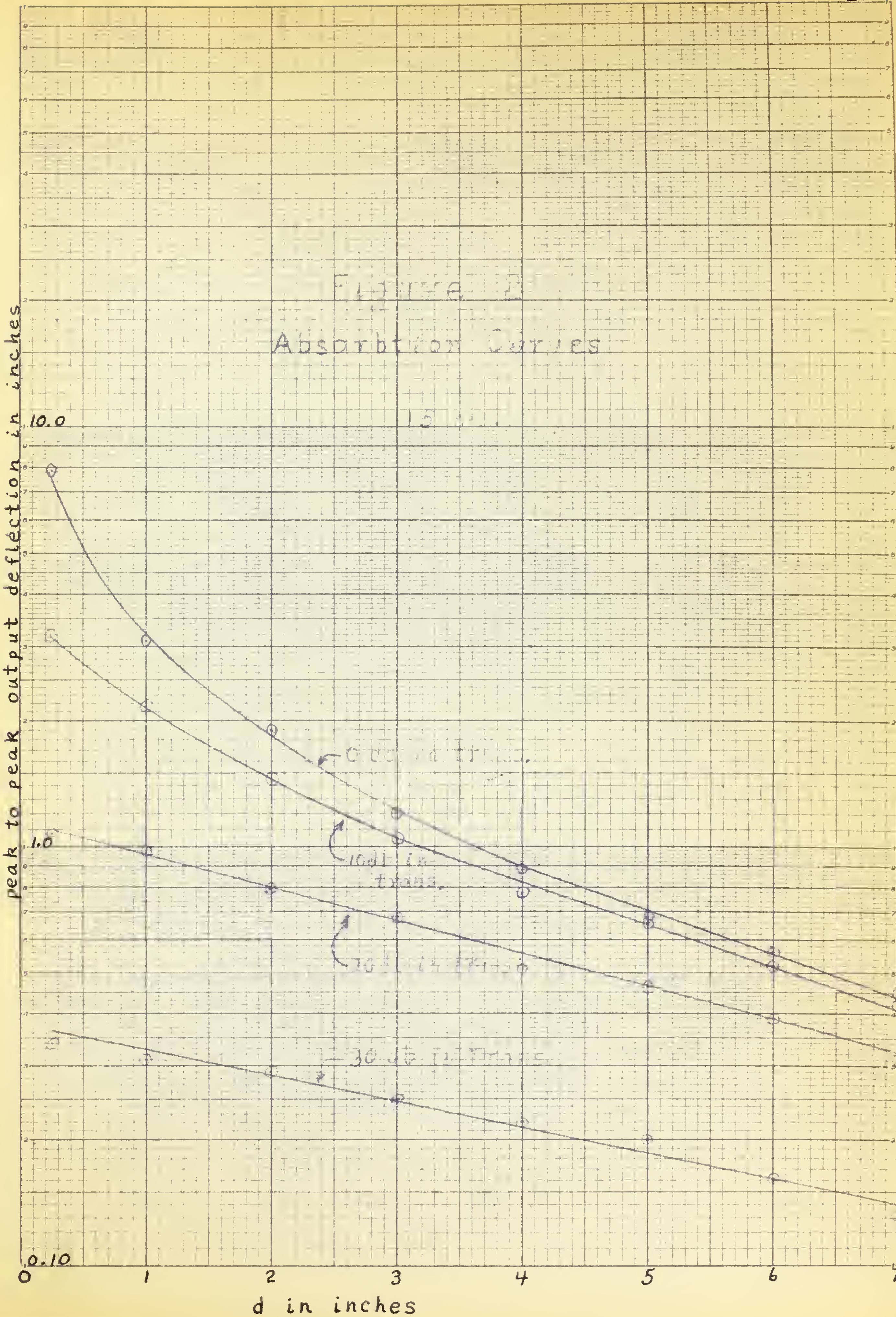


Figure 2
Absorbtion Curves
10db in trans.
peak to peak output deflection in inches
10.0
1.0
0.10
0
1
2
3
4
5
6
7
d in inches

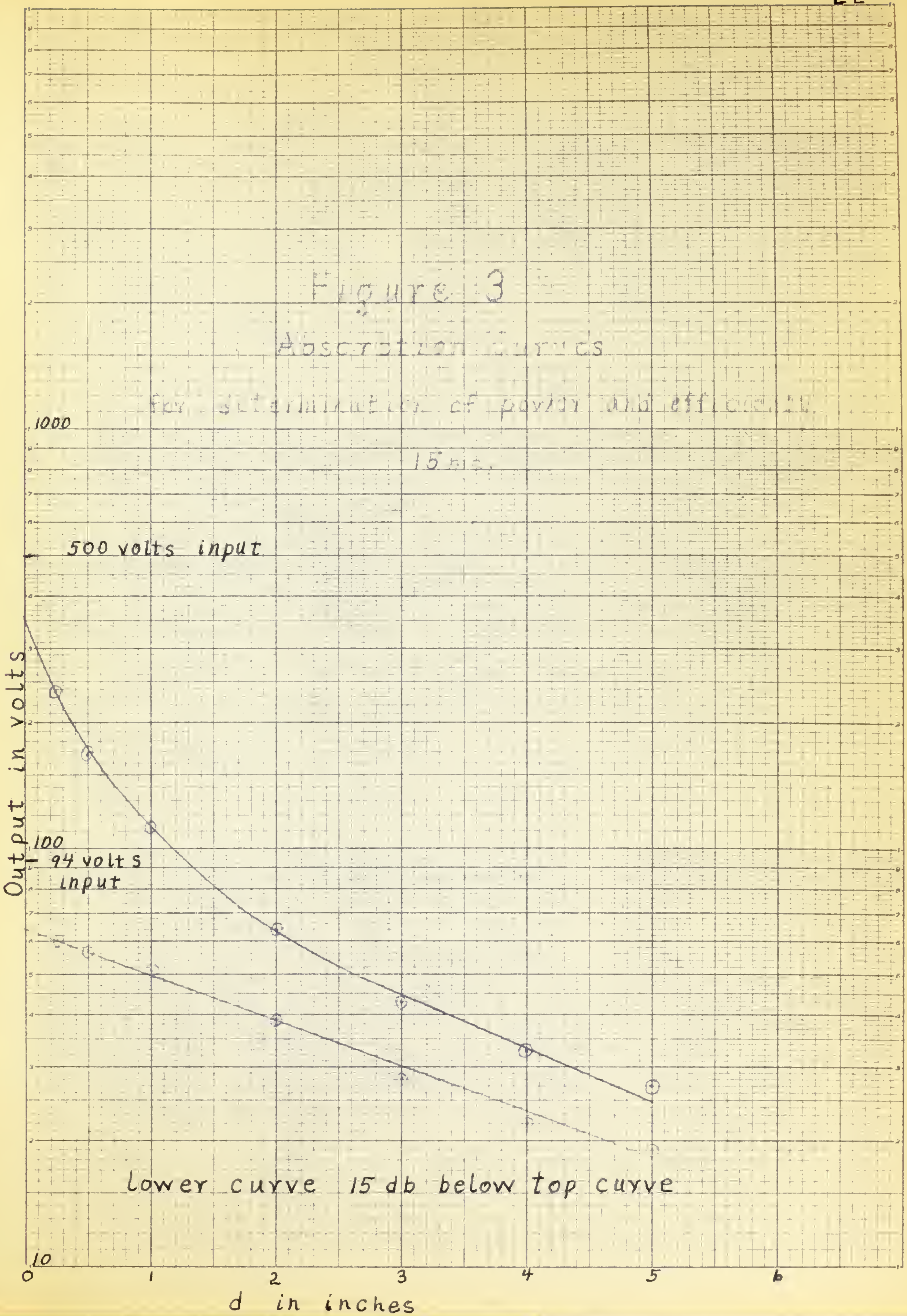


Figure 3
1000
500 volts input
100
94 volts input
Output in volts
lower curve 15 db below top curve
10
0
1
2
3
4
5
6
d in inches

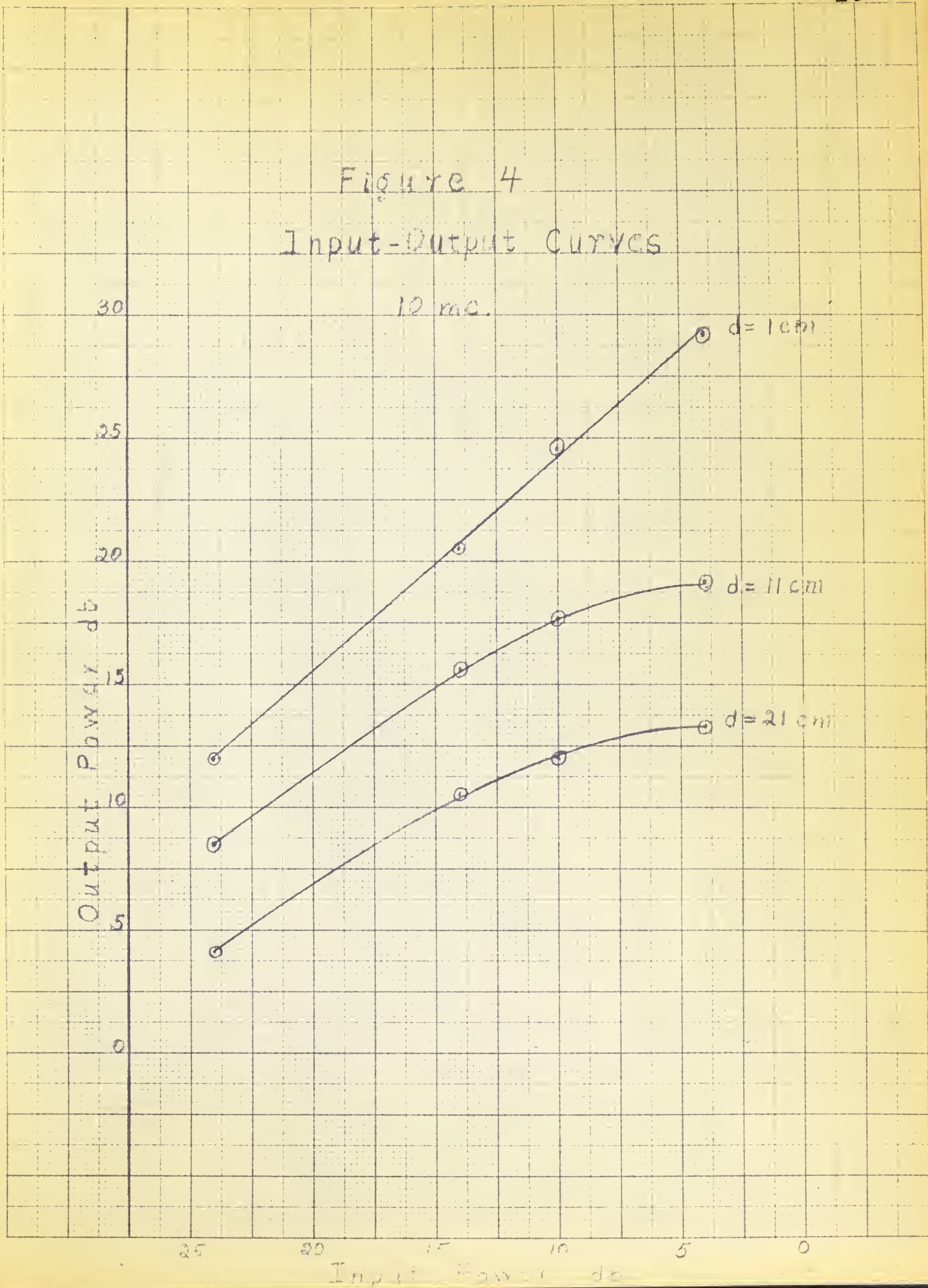


Figure 4
Input-Output Curves
10 mc.
d = 1 cm
d = 11 cm
d = 21 cm
Output Power db
30
25
20
15
10
5
0
25
20
15
10
5
0

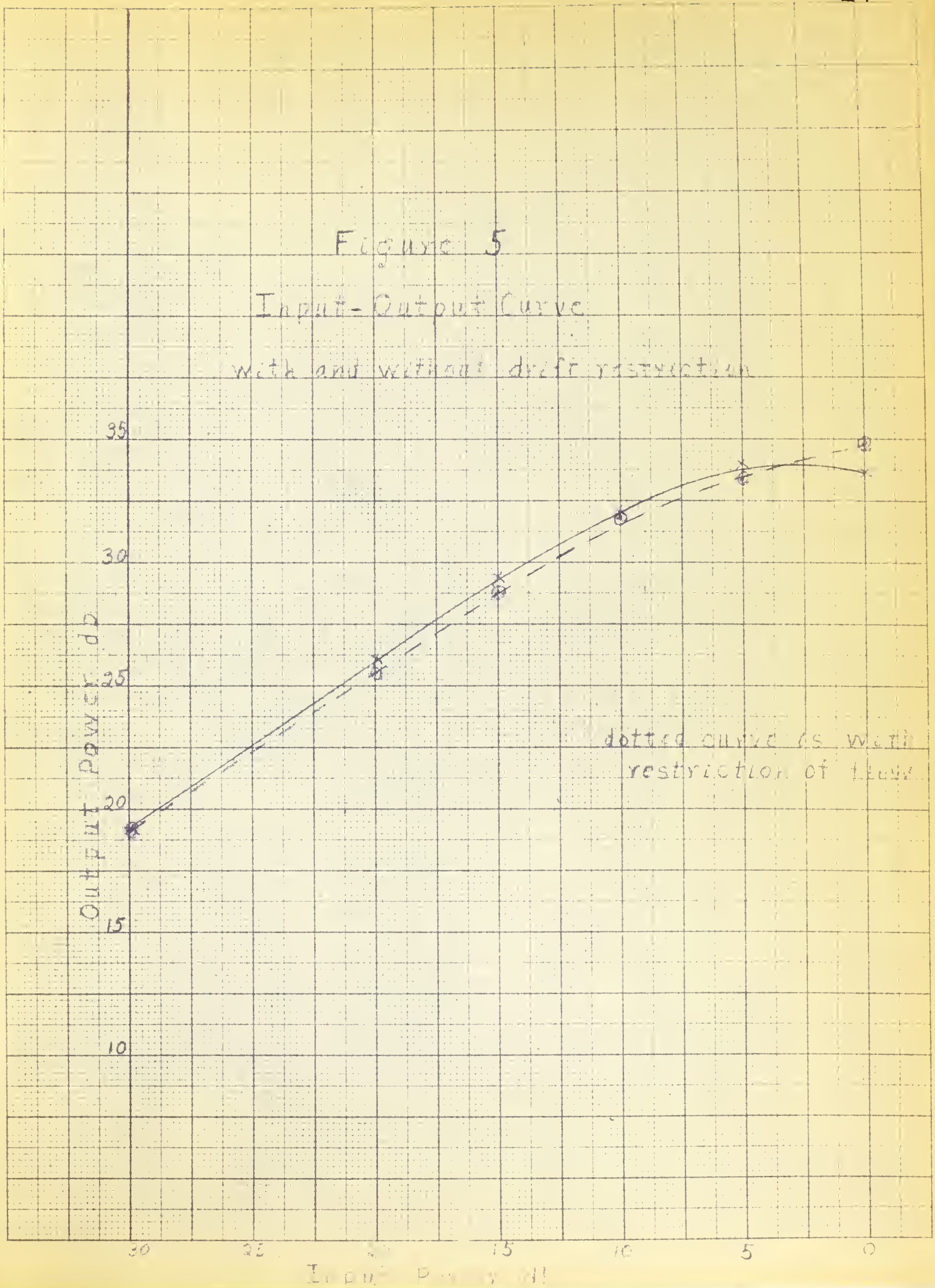


Figure 5
Input-Output Curve
with and without drift restriction
dotted curve is with
restriction of flow
Output Power db
35
30
25
20
15
10
30
25
20
15
10
5
0
Input Power

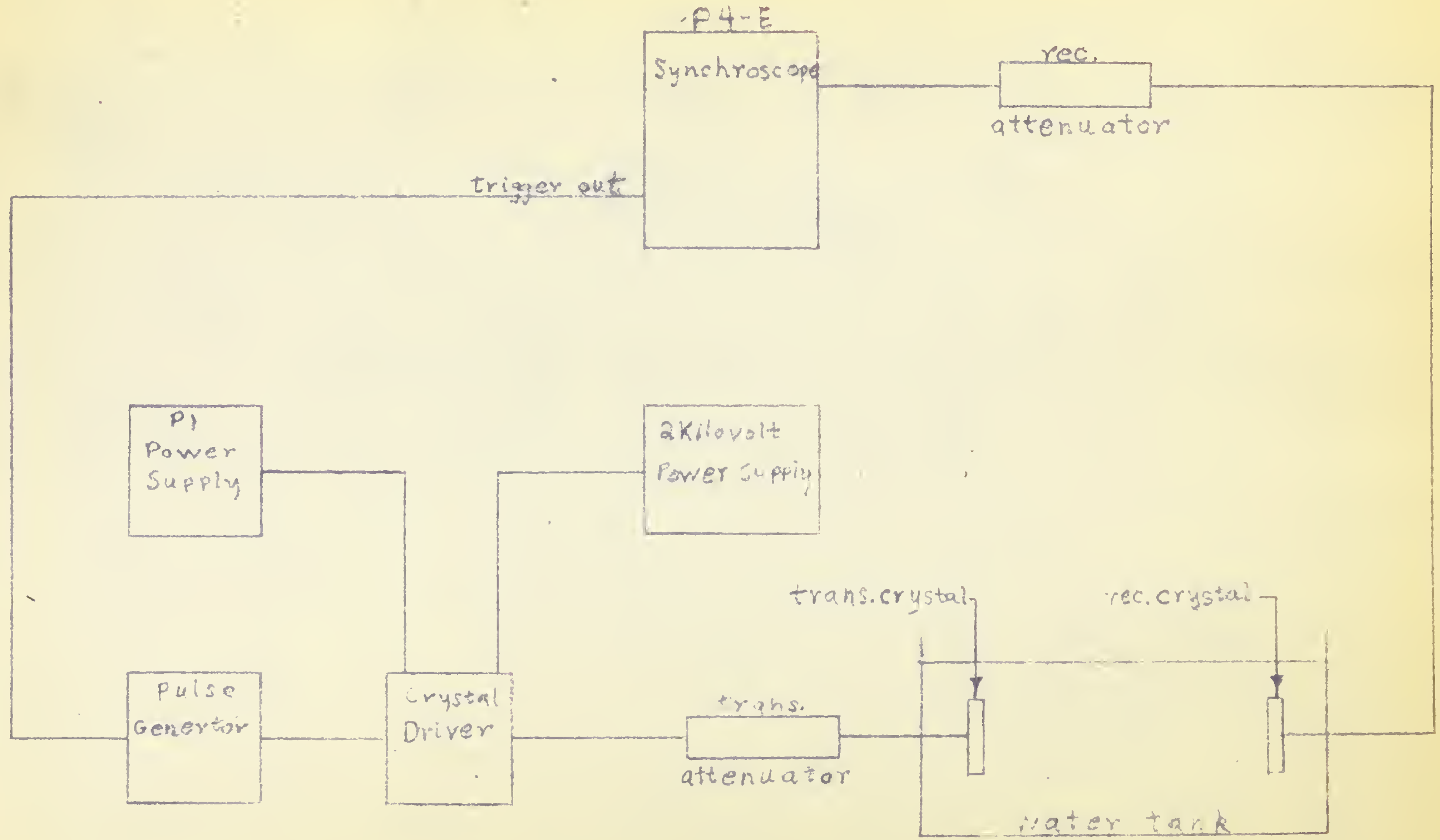


Figure 6

Blocked diagram

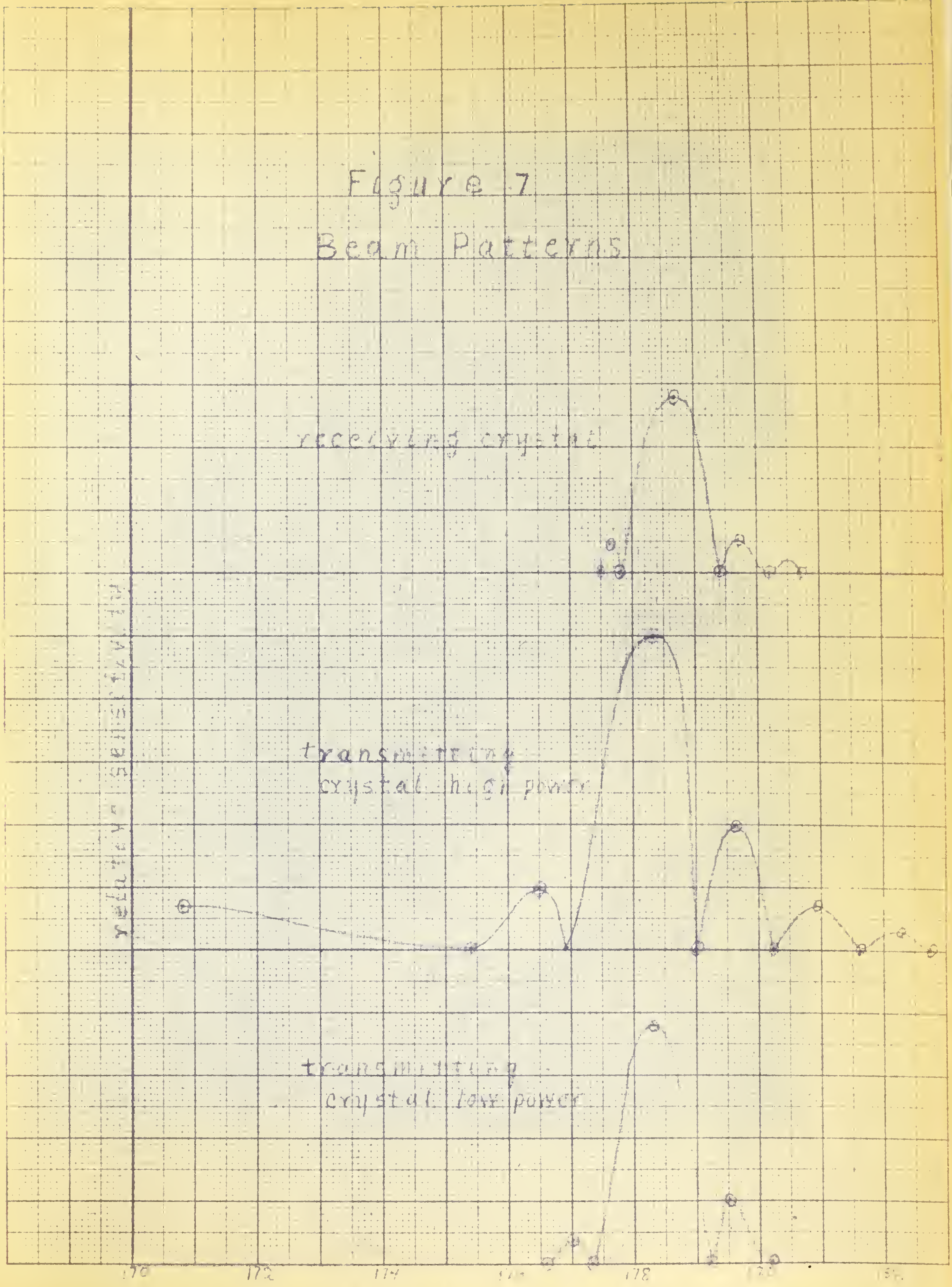


Figure 7
Beam Patterns

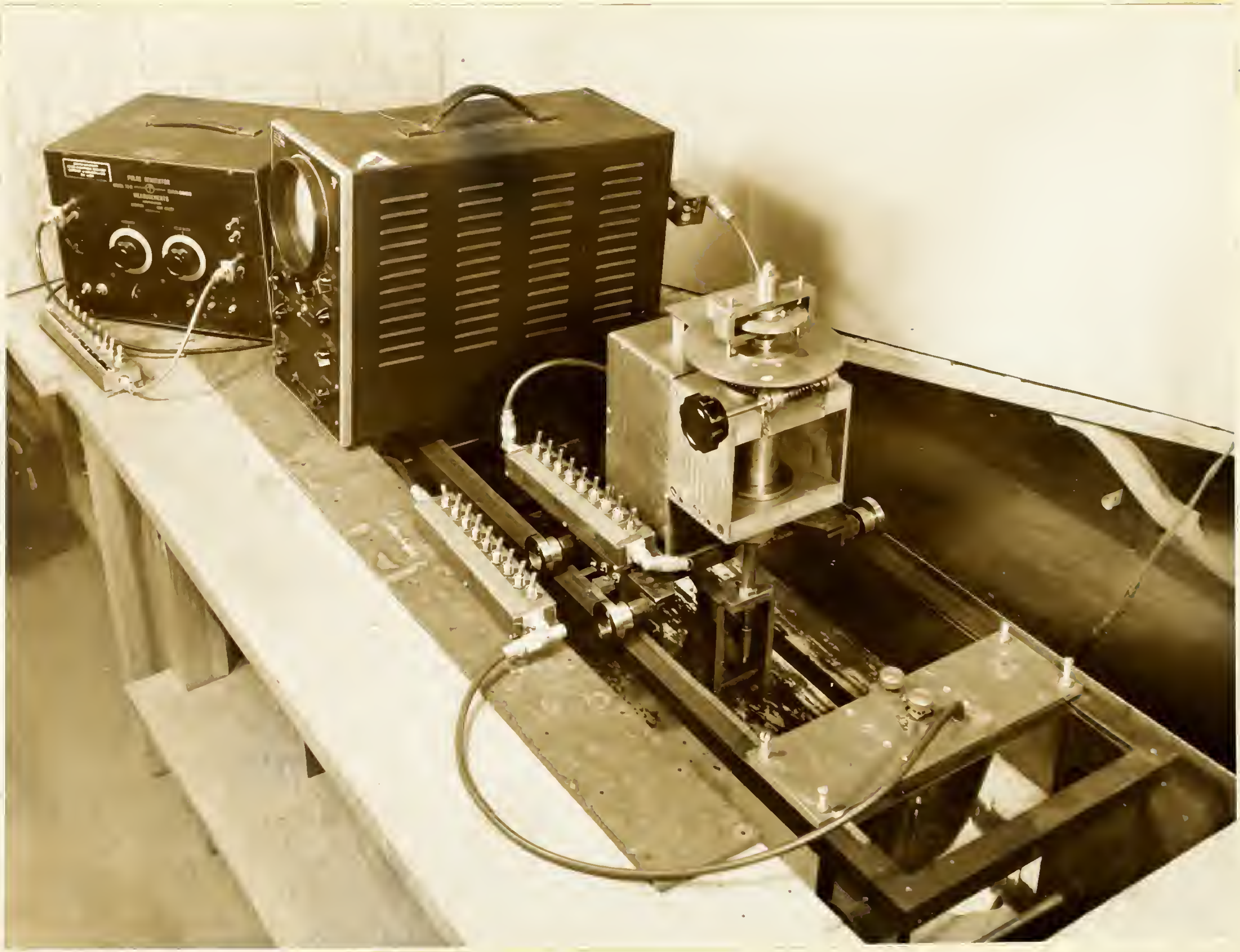


Figure 8. Bench equipment setup.

Figure 9. Crystal Holder.

Scales for azimuth and elevation are shown at top.

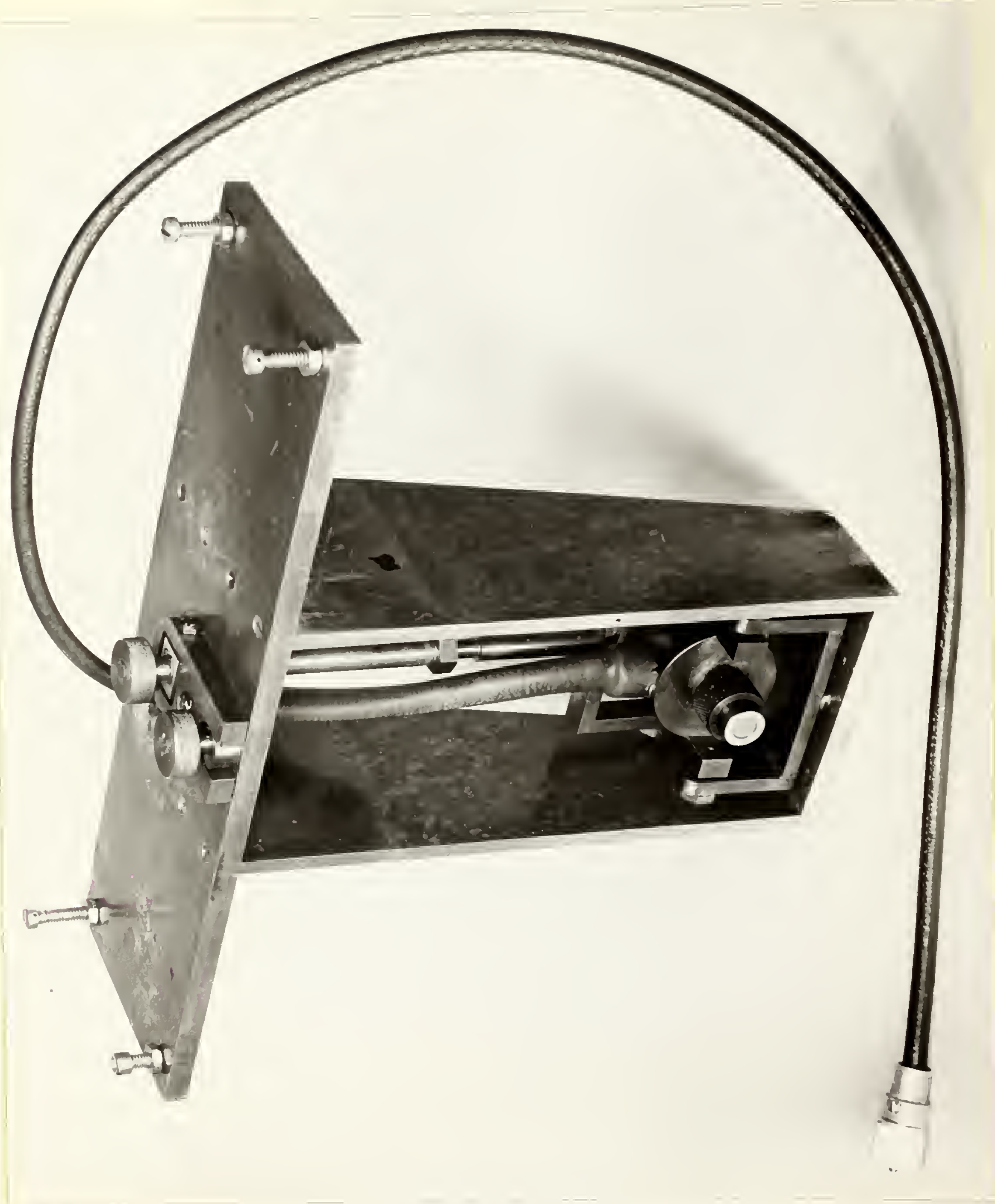


Figure 10. Crystal Holder.

Figure 11.

Crystal Cartridge Assembly.

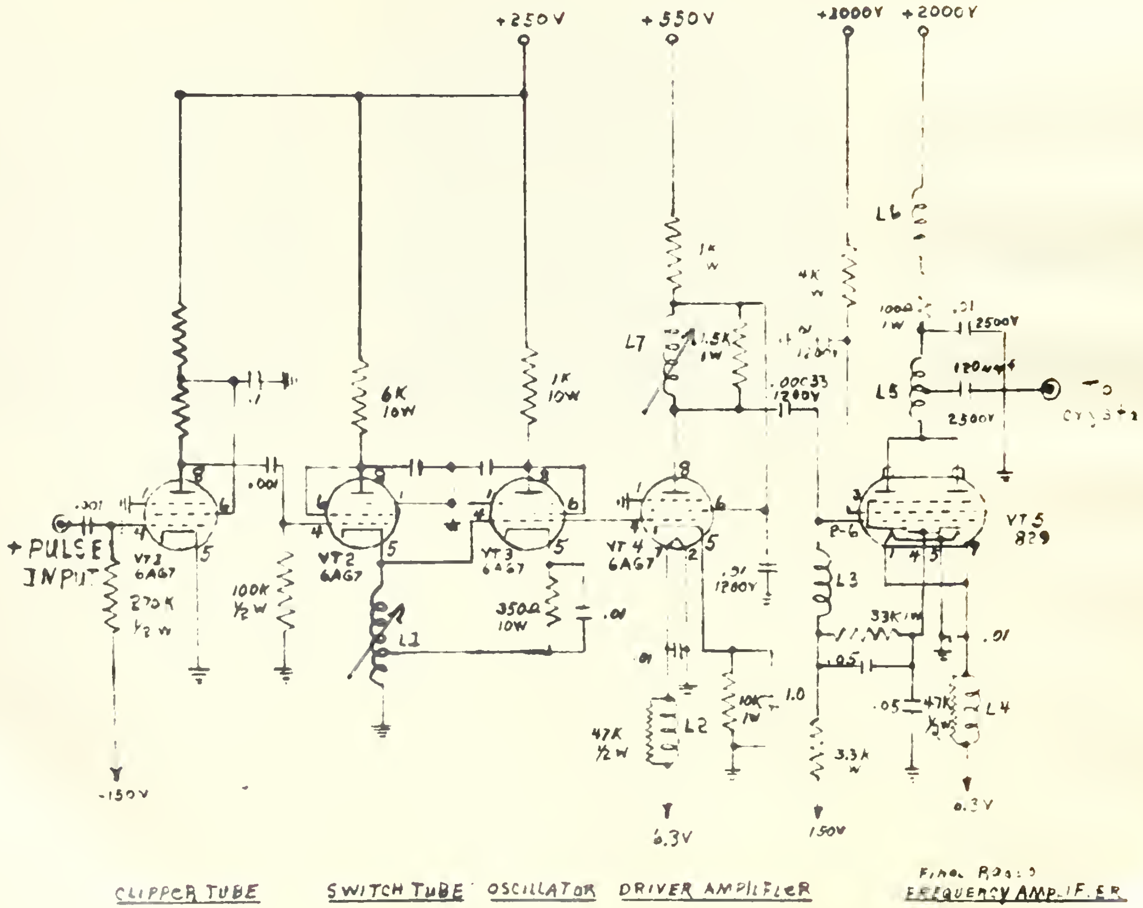
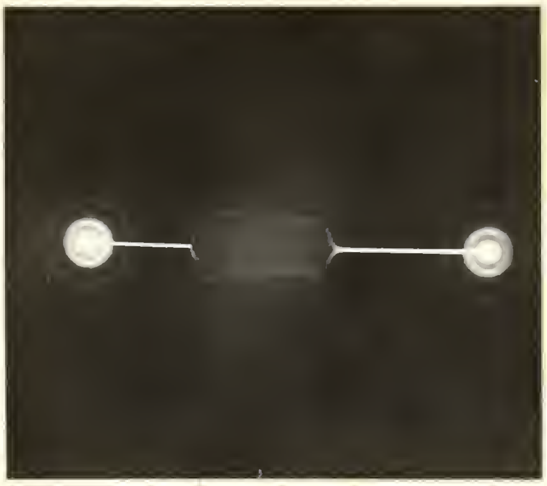
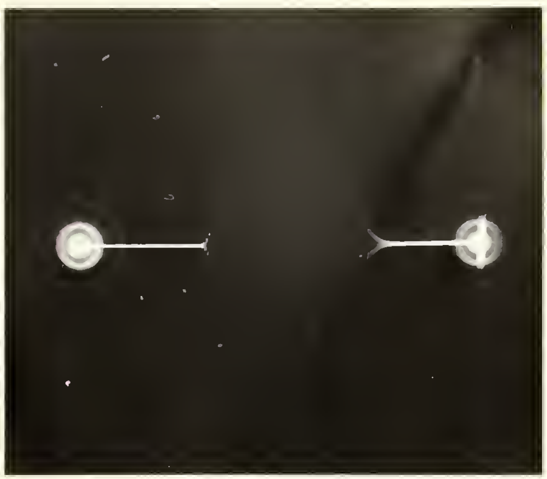


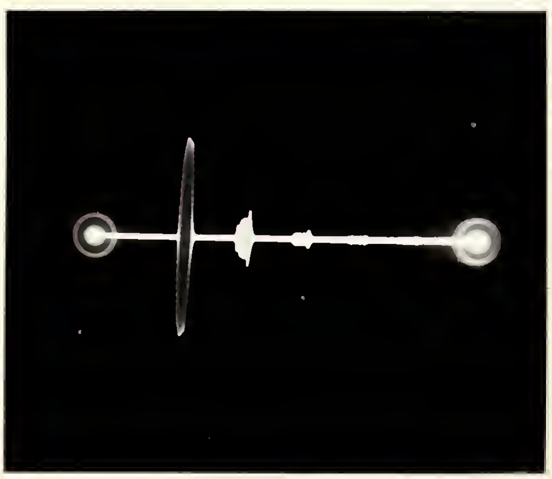
FIG. 12 MODIFIED R-2A CRYSTAL DRIVER



Input wave form for a two micro-second pulse at the input to the transmitting crystal matching network.



Output wave form for the same pulse.



Output wave form with a sweep speed of 30 micro-seconds/inch showing multiple reflections between crystals.

Figure 13 Scope Pictures

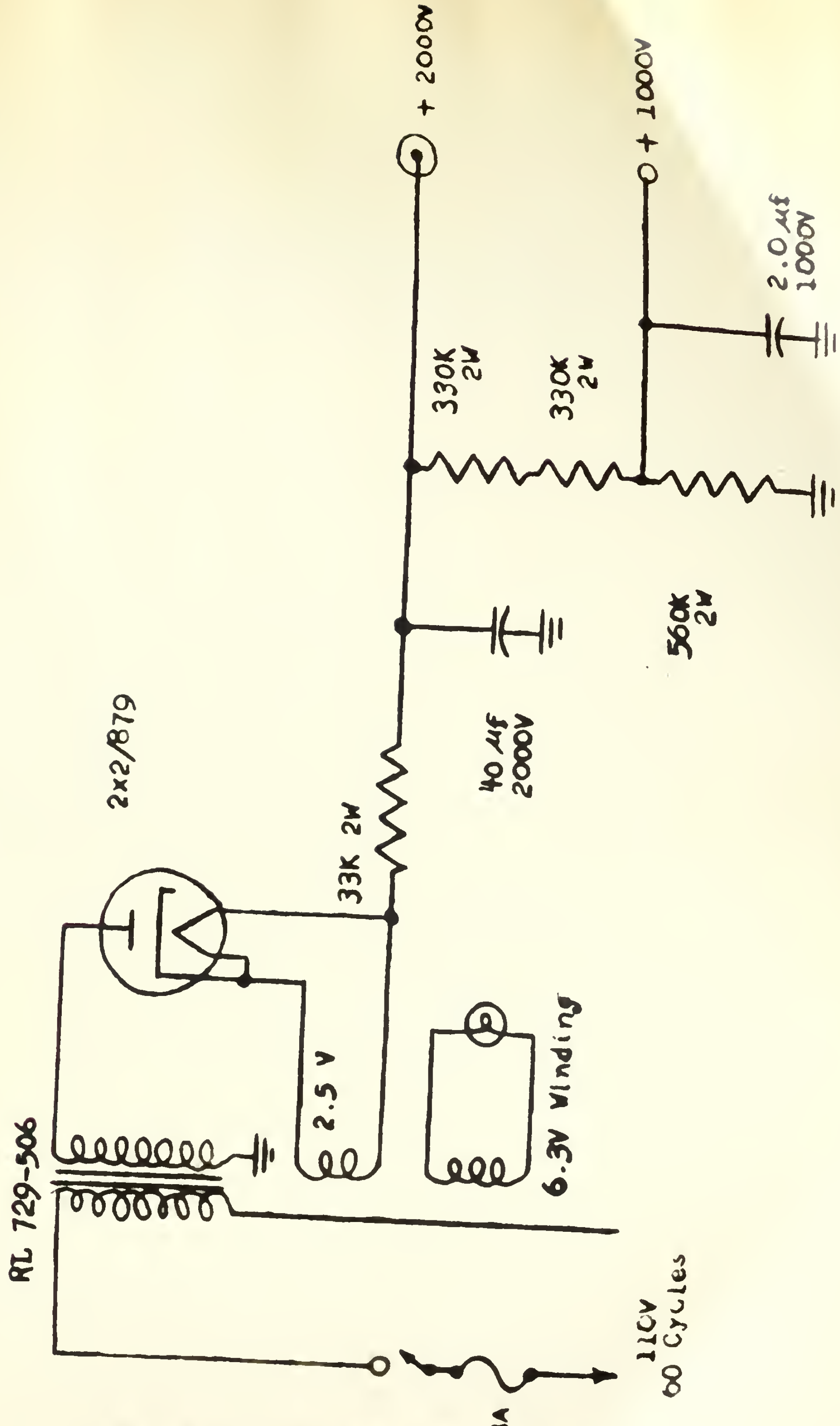


Fig. 14 2-Kilovolt power supply

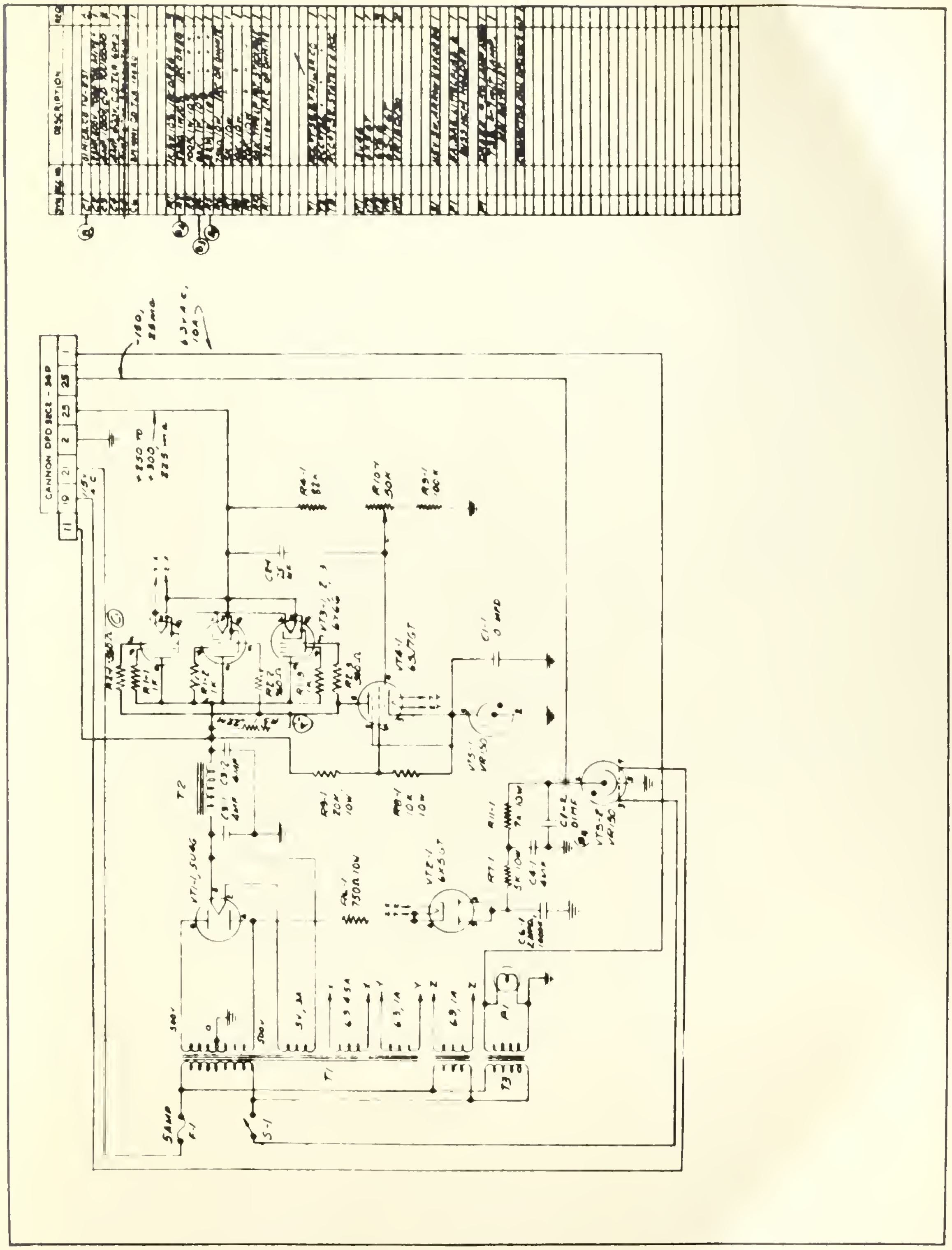


Fig. 15
SCHEMATIC DIAGRAM OF POWER SUPPLY, TYPE P-1

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ABSTRACT

The phenomena of cavitation limits the power transmitted in water, but it is known that if the sound is transmitted in pulses, the power required to produce cavitation increases with decreasing pulse length. In many liquids including water, the increase in power to produce cavitation has been investigated for pulse lengths of 10 milliseconds and longer.

In this report an attempted investigation of the cavitation point for pulse lengths near one microsecond was made. Some nonlinear characteristics that were previously reported as cavitation were found. These characteristics are not in complete agreement with those accompanying cavitation as reported in other sources, but they seem to arise from increased absorption caused by the dissassociation of the complex molecules of water by the sound waves.

Most of the equipment used was designed by the Radiation Laboratory at M.I.T. and was modified for this experiment. Point to point measurements were made in preference to the reflection method as usually used with pulse measurements.